

Evaluation of Real-Time, Long-Range, Precise, Differential, Kinematic GPS Using Broadcast Orbits

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BIOGRAPHIES

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ABSTRACT

A kinematic, differential GPS real-time navigation system is being developed at the NSWCDD research establishment of the US Navy in Dahlgren, Virginia. The immediate objective is to achieve highly precise geolocation of ground objects using an advanced digital airborne camera flown at great distances from the nearest GPS ground station. Here the kinematic solution is used to locate and orient precisely the camera in space, by updating an inertial navigation unit attached to the camera. The main GPS data are the double-differenced, ionosphere-free combination of the L1 and L2 carrier-phases, or Lc. The real-time system has two major components. The first one, data retrieval, is for collecting, transmitting, and making available for analysis the receiver data from the vehicle and from the sites of a network of reference

stations. The other component, data processing and navigation, is for editing, correcting and analyzing the data to obtain the precise position of the vehicle with a minimum of delay. The approach followed in this work is to double-difference the receiver data, and to use the Navigation Message broadcast satellite ephemerides, while estimating their errors. The system's real-time position accuracy has been evaluated using data from different test data sets, including two aircraft flights. The trajectories calculated with the real-time navigation Kalman filter are compared to precise solutions, relative to a nearby receiver, with correctly fixed carrier phase ambiguities. Early results indicate that decimeter-level positioning at more than 1000km from the nearest base station can be achieved in real time, once the filter has converged sufficiently, and that this accuracy can then be maintained over many hours.

INTRODUCTION

The ability to use GPS to find accurately the present position of a vehicle far from any base station, opens the way to many interesting forms of wide-area remote sensing in real time. Applications include: Geolocating inaccessible landmarks from the air with digital cameras, mapping terrain with scanning radar, lidar, or sonar, the advance warning of natural hazards such as tsunamis, or the automatic steering of vehicles for precision farming. The approach adopted here is real-time differential kinematic positioning. For this to work, data from one or more reference ground receivers and the roving receiver on the vehicle have to be collected and transmitted to the place where the actual navigation solution is carried out. This requires a data processing system with communications and control software that can interrogate the receivers, get and store their data and related information, and pass that to a navigation program as needed, to estimate the current vehicle position. This position then has to be sent to the applications that need it. Control signals have to be exchanged between all these processes to avoid conflicts

and ensure the smooth and uneventful operation of the whole system. Also, some measures have to be taken to mitigate the effect of delays in data reception, or latency. Our navigation routine, here called "real-time IT (Interferometric Translocation)", is used to compute precise estimates of the position of the vehicle. To achieve decimeter-level accuracy over distances of more than 1000 km, many additional unknowns must be estimated together with the vehicle trajectory. As implemented here, we use a kinematic adaptation of the ultra-precise, very-long-baseline GPS technique developed in the 1980's and 90's for static geophysical surveys [1], [3]. The additional unknowns are: Errors in the broadcast ephemerides, zenith-delay errors in the tropospheric refraction correction, and the biases in the carrier phase ionosphere-free combination (or Lc) caused by the L1 and L2 integer-cycle ambiguities. It is also necessary to correct for the solid-earth tide movement at the fixed sites and, optionally, at the vehicle. In general, the L1 and L2 ambiguities cannot be resolved over very long baselines, so the Lc biases are "floated" (estimated as real-valued unknowns). All these unknowns often number between 50 and 150 (even when inactive ones are "recycled", to make way for those newly active, without increasing the total demand on computing resources). So the position of the vehicle can begin to be obtained precisely only after enough data have been assimilated in the filter to estimate all of them [2]. That could take the better part of one hour if only the carrier phase is used. Depending on the situation, this period of convergence could be speeded up by using pseudo-range reasonably free of multipath, or placing a variety of constraints on the solution. These might include, among others, a mean sea-surface variability constraint in the case of ships or buoys [4], [5] and some integer ambiguity resolution over initially short baselines, or over longer ones if sufficiently precise ionospheric corrections are available [6], [7]. A common approach, followed in this work, is to double-difference the observations, and to use dual-frequency data in order to eliminate the unpredictable effect of ionospheric refraction. Alternatively, it is possible to use undifferenced data [8], [9] but this requires access to near-real-time estimates of both satellite orbits and clock errors that must be considerably better than those broadcast in the Navigation Message [10].

DESCRIPTION OF REAL-TIME SYSTEM

Real-time data acquisition and flow control

The overall flow of data is illustrated in Figure 1. Communications with reference and roving receivers is handled by the GRIM software, which also stores the data. Program COMSYS retrieves and passes this information to the real-time IT software (described in next section). IT cleans up the data, and then estimates the precise position of the vehicle. A distribution routine makes that estimate available to other processes, including a GPS/INS

navigation solution, for a GPS position update of its Kalman filter.

Data from GPS receivers are initially received in real-time by GRIM, which is Commercial Off the Shelf (COTS) software produced by The XYZs of GPS, Inc. This software is capable of receiving GPS data from a wide variety of receivers including Ashtech, Leica, and Novatel models. The data can be received through a variety of mechanisms, including a direct connection through a Comm port, a modem connection through a Comm port, or a radio modem connection through a Comm port. For each GPS receiver, a dedicated GRIM is needed. The GRIM software then exports the GPS data via a Windows socket to the first part of the COMSYS software, entitled the COMSYS C++ module, which is thread independent from the "IT" software. This module receives, in real-time, observation, position and navigation data from GRIM in addition to health messages, status messages, and other informational messages. The COMSYS C++ module controls and interrogates all the GRIM threads, and passes the received GPS data and other information via memory shared to a COMSYS Fortran 90 subroutine in IT.

COMSYS converts the receiver observation and navigation data collected by GRIM to the RINEX format. The COMSYS C++ thread receives the information from GRIM via a Windows socket, and passes three main pieces of information to IT. The first is RINEX-2 header information on each receiver, with the site name, coordinates, epoch interval, wavelength factors, and number and types of GPS observations. This information is passed along at startup of the program and is expected not to change during the course of a navigation solution. The second piece of information is the GPS measurements. The data are passed along, immediately, at every epoch they are received. A number of these observations are also buffered in memory and passed along together if there is a backup in reading of the data by the COMSYS Fortran subroutine. The third piece of information passed by COMSYS is the navigation data. This data is passed along at startup for each GPS receiver and whenever new ephemerides are received. The COMSYS Fortran subroutine is called by the IT thread, which is written in this language. It constantly checks for new data being provided by the COMSYS C++ thread. When it detects new observation data from the rover GPS receiver it passes this data on to the main IT thread, and attempts to find observation data from each reference receiver for the same epoch. If unable to do so, it passes along the most current observation data from each reference receiver. It also passes various messages between the main IT thread and the COMSYS C++ thread to better coordinate their operation (this part is under development). Once the IT thread has generated a precise position for an epoch, it passes this data on to a data output subroutine. The purpose of this output module is to communicate, in real-time, position and covariance information via memory mapping to a data distribution program. This data distribution program then passes along this information to

other programs that need it. Currently, the primary user of this program is a real-time GPS/INS Kalman filter, which

communicates with the data distribution program through Windows sockets.

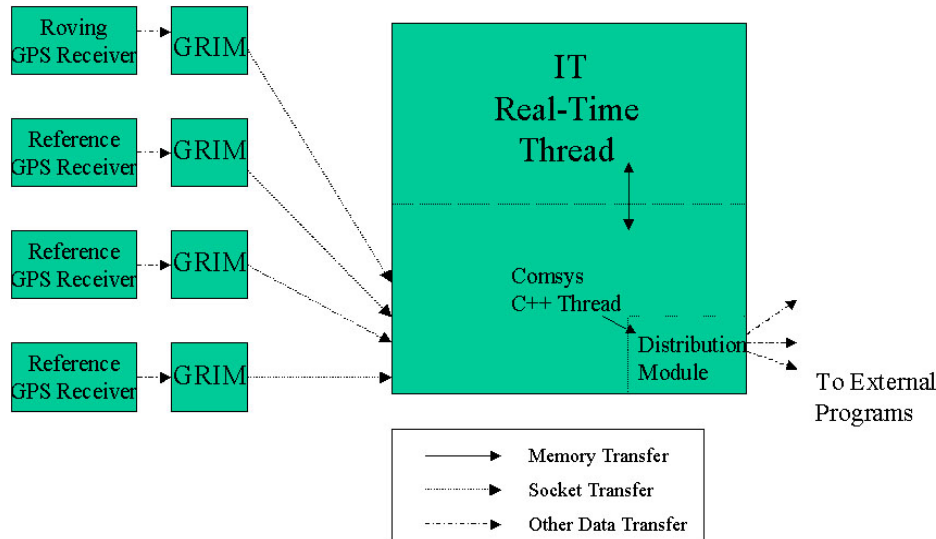


Figure 1: Real-time data from GPS receivers is controlled and received by GRIM, and then passed on by COMSYS to the precise navigation “IT” thread, and on to other modules of the system, such as a INS/GPS attitude and position estimator.

Precise, long-range kinematic GPS software

The program for Interferometric Translocation, or “IT”, was originally developed by the first author, to post-process GPS data, obtaining precise, long-baseline, kinematic and static off-line solutions. Numerous tests of this software, such as those described in [11], have shown that, with enough time to fully converge the Kalman filter, the likely 3-D precision is 5-10 cm, depending on data quality and on satellite/receiver geometry. For the NSWCCD project, IT has been modified to create a real-time version of comparable precision. Since the GPS satellite orbits and clock corrections available in real time for this project, at the moment, are those broadcast with the Navigation Message, the estimation of orbit errors during the kinematic solution is a particularly useful feature inherited from the original software. During the development of the real-time IT, many corrections and improvements have been ported back to the off-line version, so this one has been improved as well.

Post-processing IT has been written for UNIX (including LINUX and FreeBSD) and ported to Windows. The real-time IT runs under Windows (9x, NT, 2000). It might be ported to UNIX-like systems in the future.

The original IT has a Kalman filter and smoother least-squares solution procedure; the real-time version uses the same Kalman filter and no smoother, and it is based on the same error-state dynamics. The filter is updated with compressed data (or “normal points”), to reduce drastically the number of updates, the computing time, the amount of data passed from filter to smoother in post-processing, and the arithmetic round-off error propagation [12]. The data

are prepared by the real-time pre-processing routines, that delete bad data, correct phase cycle slips, correct for the effect of transmitter phase-windup, and correct tropospheric refraction (using the Niell model). Besides vehicle coordinates, the unknowns solved for include: Orbit errors (initial position, velocity, and miss-modeled accelerations), reference station coordinate errors, tropospheric refraction correction errors, and Lc phase biases. The orbit errors treatment is based on analytical orbit theory [17]. Both carrier-phase and pseudo-range are processed in the navigation Kalman filter using complete observation equations. To mitigate the effect of data latency, the observations from the fixed receivers (especially now that SA has been set to zero) can be extrapolated, if necessary, to the epoch of the most recently available rover observations. So the latency in the navigation solution is virtually the same as that of the rover data.

The observation equations, at each epoch, are linearized about a nominal position of the vehicle determined from pseudo-range data only, with *a priori* standard deviations of 100 m per coordinate, and “white noise” or “zero-memory” dynamics (i.e., a purely kinematic treatment). The *a priori* values of the carrier-phase Lc biases are the differences of instantaneous, double-differenced phase and pseudo-range observations. Each bias has a 10 m *a priori* standard deviation, and is treated as a constant (assuming all cycle-slips have been properly corrected by the real-time pre-processing subroutines). For the broadcast orbit errors, the *a priori* value for each initial position and velocity component is zero, with standard deviations (STDs) of 4 m and 0.1 mm/s, respectively.

Acceleration errors are treated as piece-wise constant in the radial, along, and across-track directions, with *a priori* STD of 10^{-9} m/s². They are allowed to change value randomly every 20 minutes. Each zenith delay error state is a random walk with an initial *a priori* value and STD of zero and 0.1m, respectively, driven by ~ 2 cm/(hour)^{-1/2} of process noise.

GPS/INS integration

The GPS carrier phase measurements have very good long-term information on the absolute position of the vehicle: The typical rate of drift from the true position, in a good kinematic solution, is of a few centimeters per hour. The acceleration and orientation measurements of an inertial navigation system (INS) have very good short-term information on changes in vehicle velocity, position, and attitude. With a much higher data rate, it can accurately fill the gaps in the trajectory left by the less frequent GPS position fixes. Its long-term precision, however, is usually quite poor, with drift rates that can be as high as tens of meters per second in position, and several degrees per hour in attitude (depending on the quality of the INS). This can be reduced considerably through sensor calibration, and one way of doing this continuously is to use GPS estimates of position as additional data, when updating the INS Kalman filter. By implicitly comparing a GPS position estimate to another made only with inertial data, the filter algorithm estimates the sensor errors responsible for their differences, and corrects the INS navigation solution accordingly [13]. In the present implementation of the overall real-time system, the GPS solution is actually made separately (with IT), and the resulting GPS position fix, weighted by its variance-covariance matrix, is used as additional data in the update of the INS filter. This is an instance of what is known as "loose GPS/INS integration". The good short-term accuracy of the INS can also be useful for validating the moving receiver data, helping detect such problems as carrier-phase cycle slips, which, if uncorrected, could cause a drastic deterioration of the GPS solution. In this way, INS can enhance the reliability of GPS and, therefore, that of the GPS/INS combination [14]. At the time of writing this paper, the real-time navigation system at NSWCCD is being integrated and tested. Preliminary live tests with fixed receivers have been made to find and resolve software conflicts. So far, some interesting navigation results have been obtained in playback mode, using pre-recorded data. An earlier test of the concept [15], also served to show the current system test-bed.

EXAMPLE I: THE FORT PENDELTON, MARCH 2001 TESTS

General Description

One of the uses of the long-range kinematic system under development is to provide position updates to the Kalman

filter of an INS unit used for determining the orientation of a digital camera flown in an airplane [16]. The particular aircraft used for the study is shown in Figure 2. The "Pelican" can be flown with a pilot on board (as during the tests considered here), or can be controlled remotely. The airplane circles a target on the ground, and from the combination of its camera images and the precise orientation and position of the camera, as described in [15], the coordinates of the target can be found with meter-level precision from several kilometers away. Figure 3 shows the location of the GPS receivers that collected data during several flights. Several of the distant receivers belong to the Continuously Operating Reference Stations (C.O.R.S.) run by NGS (NOAA), which archives their dual-frequency data, at five-second (as well as longer) intervals, in public files that can be downloaded over the Internet. The flights considered here took place over Fort Pendelton, in Southern California, in March 2001. Figure 4 displays the flight-path during one of them, when the "Pelican" was circling ground targets at a nearly constant height of some 1350 meters. Figures 5 and 6 show comparisons between the trajectories of the antenna of the GPS receiver on the "Pelican", relative to a nearby ground station (computed independently, in post-processing, with L1 and L2 ambiguities resolved), used as "truth", and the same trajectories computed with the real-time procedure relative to the distant receivers. Dual-frequency pseudo-range and carrier phase data were collected, at the rate of 1 Hz, aboard the "Pelican" and at the nearby local reference station (LCAC).

The local reference station data were used only to generate this short baseline solution for comparison purposes and were not included in the long baseline real-time processing evaluation. Because of problems handling pseudo-range with considerable multipath (now being addressed), only the carrier-phase data were used in the kinematic solutions.



Figure 2. The "PELICAN" aircraft

March 23rd Flight

Four distant receivers at Fort Stevens, Oregon (FTS1), Cape Mendocino, California (CME1), Price, Utah (PUC1), and Scottsdale, Arizona (COSA) were used to position the "Pelican" in a flight that took place on March 23, 2001.

In the simulated real-time processing, the data were treated as if they were arriving in real-time, although they were actually stored on disk, and played back one epoch at the time. The broadcast GPS orbits were used, with their errors estimated in the navigation solution. They were also read in from disk, and treated as if they were arriving in real time.

Because of the location of these sites (Figure 3), the baseline lengths from the test site (near LCAC) to these reference stations were approximately: 1500 km for FTS1, 1000 km for CME1, 1000 km for PUC1, and 530 km for COSA. All four of these sites are part of the CORS network. Both the CME1 and the FTS1 sites were running Ashtech Z-XIIs with data collected at 0.2 Hz. The PUC1 site was running a Trimble 4700 with data collected at 0.2 Hz, the COSA site was running a Trimble 4000 with data collected at 0.2 Hz. The Pelican aircraft had an Ashtech Z-XII with data collected at 1 Hz.

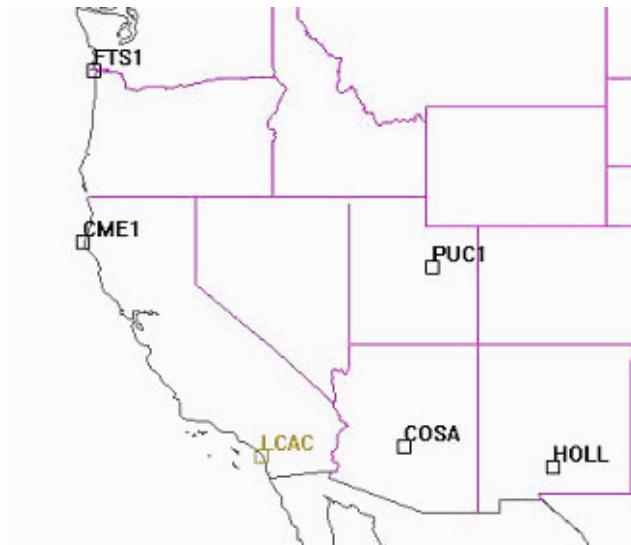


Figure 3. Local (LCAC) and distant fixed receivers.

Figure 5 shows the Height, East, and North differences (in meters) between the long baseline “real-time” solution and the accurately post-processed short-baseline solution. Table 1 shows the statistics of the differences between the two solutions. Once the differences become less than 30 cm per component (in this one case, after 23 minutes), a reasonable degree of filter convergence has been achieved. From that time on, the mean error per component is 7 cm or better, while the estimated standard deviation per component (or rms variation about the mean) is 17 cm or better.

March 25th Flight

Two distant receivers at Holloman Air Force Base, New Mexico (HOLL), and Fort Stevens, Oregon (FTS1), were used to position the “Pelican” in a flight that took place on March 25, 2001. This was done also in simulated real-time processing, as explained in the previous example. Figure 3 shows the location of the reference sites used, as well as the local (short-baseline) test site (LCAC). For March 25, the baseline lengths from the test area to the distant reference sites were, approximately, 1000 km for HOLL and 1500 km for FTS1. The FTS1 site is part of the CORS network. Both the HOLL and the FTS1 sites used Ashtech Z-XIIs with data collection at 0.2 Hz, while the Pelican aircraft had an Ashtech Z-XII collecting data at 1 Hz.

Figure 6 shows the differences between the long-baseline “real-time” solution versus the accurate post-processed short-baseline solution, or “truth”. A rapid filter convergence period can be seen at the beginning, with deviations from “truth” of less than 50 cm per component after 5 minutes, and less than 30 cm per component after 16 minutes. Table 2 shows the statistics of the differences between these solutions, after the first 6-minutes of the convergence period. As can be seen, the mean is better than 10 cm for each horizontal component, and is 20 cm for the vertical component. Standard deviations are around 20 cm or better for each component. A decline in the number of satellites available can be seen in the increasing PDOP near the end of the flight.

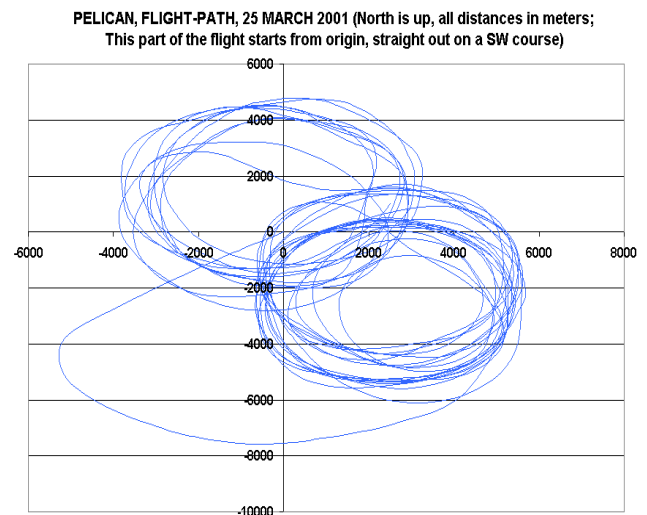


Figure 4. Trajectory of the “Pelican” on 25 March 2001

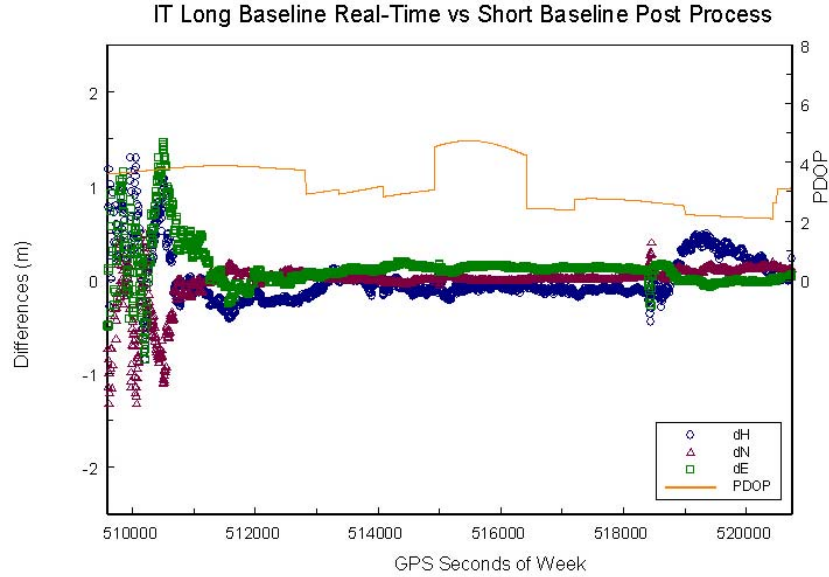


Figure 5. Differences between the real-time long baseline trajectory solution and "truth" (a post-processed short-baseline trajectory solution with fixed ambiguities) for Pelican flight on March 23, 2001. Orbits used: Broadcast (simultaneously adjusted). Carrier phase-only solution. Four reference sites; baseline lengths from 530km to 1500km.

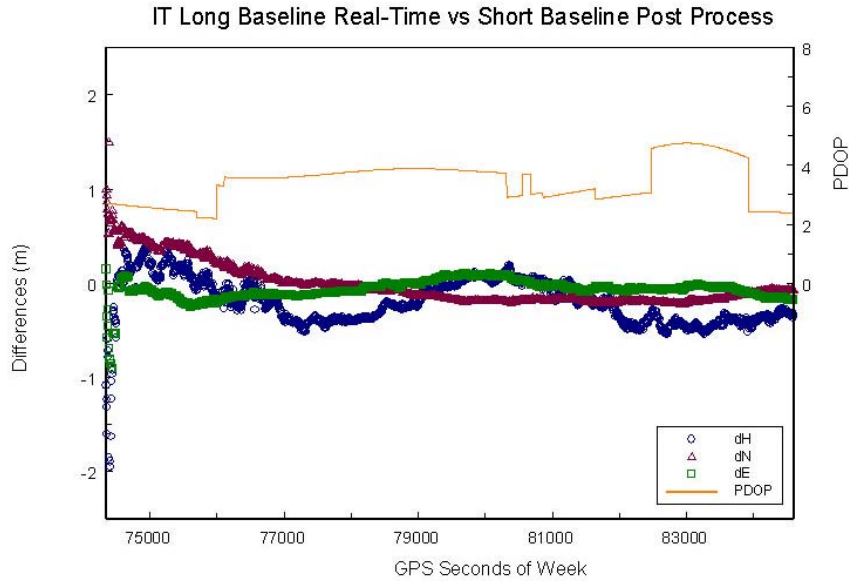


Figure 6. Differences between the real-time long baseline trajectory solution and "truth" (a short-baseline solution, as in Fig. 6) for Pelican flight on March 25, 2001. Orbits used: Broadcast (simultaneously adjusted). Carrier phase-only solution. Two reference sites; baseline lengths: 1000km to 1500km.

Table 1. Summary of differences between long and short baseline kinematic positioning, March 23, 2001.

	East	North	Vertical
Mean (m)	0.07	0.03	-0.05
Std (m)	0.09	0.05	0.17

Table 2 Summary of differences between the real-time, long baseline and the post-test, short baseline kinematic positioning, March 25, 2001.

	East	North	Vertical
Mean (m)	-0.07	-0.04	-0.20
STD (m)	0.08	0.19	0.22

EXAMPLE II: CORS SITE AT GAITHERSBURG

The data for this test were from fixed receivers at the CORS sites GAIT (Gaithersburg, Maryland), ASHE (Asheville, North Carolina), and ORO1 (Maine), with a 5-second sampling rate. The GAIT site was navigated relative to the other two.

The distances from GAIT to ORO1 and ASHE are 953 km and 613 km, respectively. The published coordinates of the CORS are generally more accurate than 5 cm. The result of comparing with them the instantaneous kinematic positions of the site over a period spanning 12 hours is shown in Figure 7. Here dH, dN, and dE are the differences in Height, North, and East. Instantaneous values are plotted at

2-minute intervals (the kinematic solution starts at 0:10 hours UTC).

The initialization period of the Kalman filter is clearly seen: It takes about 15 minutes before all three components are within one foot (~30 cm) of "truth". Once the filter converges, the differences generally stay within +/- 25 cm in height, and +/- 10 cm in horizontal position. Figure 8 shows in detail and at full-rate (one point every five seconds) the differences, from initial convergence through the 12th hour of the test. As in the case of the "Pelican" tests, this solution includes the simultaneous adjustment of the broadcast orbits.

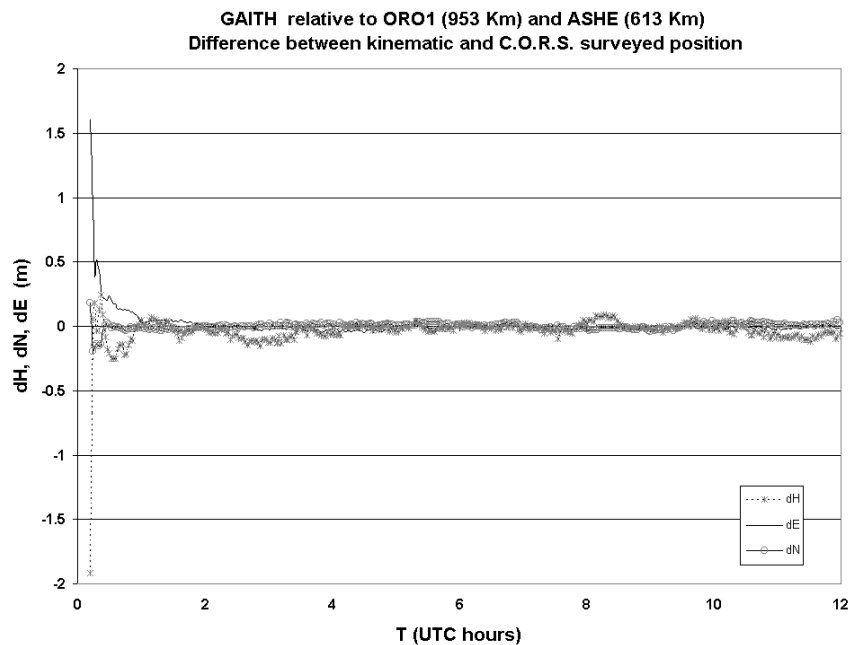


Figure 7. Differences between the long-range kinematic solution for GAIT and the precise coordinates for the marker. Orbits: Broadcast (simultaneously adjusted). Carrier-phase only solution. Two reference sites, distances shown in the figure.

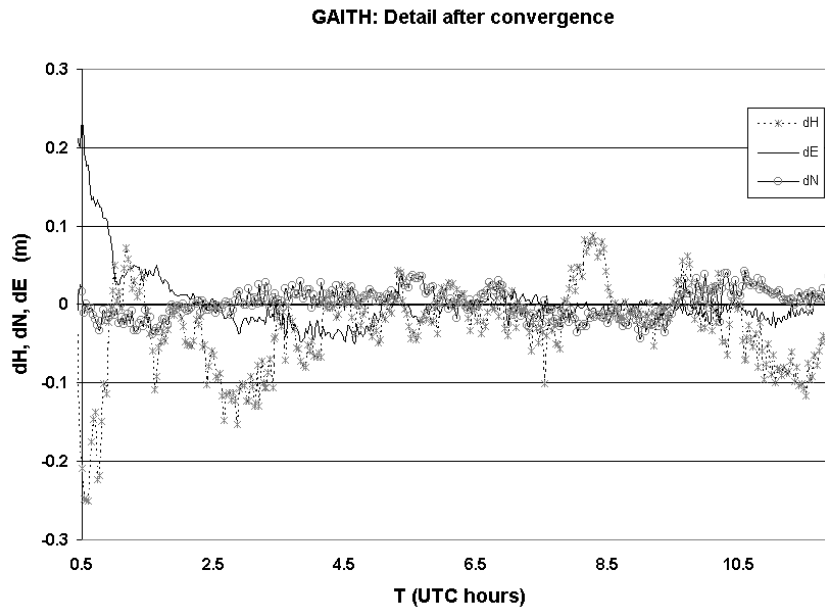


Figure 8. The kinematic solution of Fig. 7 after the Kalman filter has converged. Orbits: Broadcast (simultaneously adjusted).

CONCLUSIONS

To evaluate the real-time, long baseline kinematic software, we have examined two cases: a static platform and a moving platform. For the static platform, differences with the “truth” solution, once the Kalman filter had converged, were less than 10 cm horizontally and less than 25 cm vertically, over a period of 12 hours, using two reference stations about 600 and 1000 km away. For the moving platform, two days of flights with a small aircraft were examined. The total RMS difference (including the mean) with the precise short baseline solution was of 20 cm, or less, in East and North, and 30 cm, or less, vertically, using two to four reference sites with baselines of 500 km, 1000 km, or 1500 km. Because of multipath problems, no pseudo-range data were used in the precise solutions. Improvements to the software, now being tested, should allow better results using the pseudo-range as well as the phase data. In all the examples shown here, the broadcast GPS orbits were used, with their errors being estimated simultaneously with the trajectory and with other parameters in the Kalman navigation filter, including one residual zenith delay per receiver site, and the biases of the double-differences of the ionosphere-free (Lc) carrier-phase combination.

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